PLANAR ULTRA WIDE BAND ANTENNA WITH BAND REJECTOR

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DEDICATION

To my beloved family members, friends, and all the people who helped and supported me during this journey.

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ABSTRACT

Ultra wideband (UWB) that occupies the range of (3.1-10.6) GHz was proposed due to the progressive need of high data rates for modern applications and lack of bandwidth in lower frequencies. UWB systems have become fundamental in high speed wireless communications that are used for short range indoor applications due to their features such as low power consumption, small size, and low cost. Antennas are essential part of the UWB systems, especially planar antennas because they can be fabricated easily. But an electromagnetic interference may occur due to the existence of narrowband systems like wireless local area networks (WLANs) that operate at 5.8 GHz which is inside the UWB band. Therefore, UWB antennas should also avoid those frequencies in order to obtain more efficient operating system. Thus, special structure known as electromagnetic band gap (EBG) structures can be used as band rejecter in order to reject the interlaced band. This project focuses on EBG structures and how they can be incorporated with UWB antennas. Firstly, a new planar UWB antenna structure that operates at UWB frequency range (3.08-10.7 GHz) is presented using half ground plane method. The antenna achieved a peak gain of 5.26 dB. Moreover, it exhibits a radiation efficiency of higher than 74% over its bandwidth. Then, a study is conducted on EBG mushroom-like shape using suspended transmission line method. Next, a new EBG structure that operates at 5.8 GHz is proposed. Shortly after, the designed structures are incorporated together to perform the intended function of an UWB with a gap at 5.8 GHz. The new structure has a notch of 0.7 GHz in terms of ($S_{11} \leq -10$ dB), whereas the rejected band is 0.18 GHz. Additionally, outside the rejected band, the performance of the UWB antenna was not much affected by adding the EBG. In fact, excluding the notch, the antenna bandwidth increased to cover the range from 2.91 GHz to 11 GHz. FR4 substrate with ($\varepsilon_r = 4.3$) is used for all designs. Simulations are conducted using CST software, and all the results are presented into graphs and tables.

ABSTRAK

Jalur lebar Ultra (UWB) yang menempati batas (3.1-10.6) GHz dicadangkan kerana keperluan progresif kadar data yang tinggi untuk aplikasi moden dan kekurangan lebar jalur pada frekuensi yang lebih rendah. Sistem UWB telah menjadi asas dalam komunikasi tanpa wayar berkelajuan tinggi yang digunakan untuk aplikasi dalam jarak dekat kerana ciri-cirinya seperti penggunaan kuasa rendah, saiz kecil, dan kos rendah. Antena adalah bahagian penting dalam sistem UWB, terutama antena satah kerana ia dapat difabrikasi dengan mudah. Tetapi pertindihan elektromagnetik mungkin berlaku kerana adanya sistem jalur sempit seperti rangkaian kawasan tempatan tanpa wayar (WLAN) yang beroperasi pada 5.8 GHz yang berada di dalam jalur UWB. Oleh itu, antena UWB juga harus mengelakkan frekuensi tersebut untuk memperoleh sistem operasi yang lebih cekap. Oleh itu, struktur khas yang dikenali sebagai struktur elektromagnetik selar jalur (EBG) dapat digunakan sebagai penolak jalur untuk menolak jalur yang saling berkait. Projek ini memberi tumpuan kepada struktur EBG dan bagaimana ia dapat digabungkan dengan antena UWB. Pertama, struktur antena UWB satah baru yang beroperasi pada julat frekuensi UWB (3.08-10.7 GHz) dipersembahkan menggunakan kaedah satah separuh bumi. Antena mencapai gandaan puncak 5.26 dB. Tambahan lagi, ia mempamerkan kecekapan radiasi lebih tinggi daripada 74% sepanjang lebar jalurnya. Kemudian, kajian dilakukan pada bentuk EBG mirip-cendawan dengan menggunakan kaedah saluran penghantaran yang digantung. Seterusnya, struktur EBG baru yang beroperasi pada 5.8 GHz dicadangkan. Sejurus kemudian, struktur yang dibina digabungkan bersama untuk melakukan fungsi yang UWB dengan jurang pada 5.8 GHz yang diperlukan. Struktur baru memiliki takik 0.7 GHz dari segi (S_{11}≤-10 dB), manakala jalur yang ditolak adalah 0.18 GHz. Tambahan lagi, di luar jalur yang ditolak, prestasi antena UWB tidak banyak dipengaruhi oleh penambahan EBG. Sebenarnya, tidak termasuk takik, lebar jalur antena meningkat untuk meliputi julat dari 2.91 GHz hingga 11 GHz. Substrat FR4 dengan ($\varepsilon_r = 4.3$) digunakan untuk semua reka bentuk. Simulasi dilakukan menggunakan perisian CST, dan semua hasilnya dipersembahkan ke dalam grafik dan jadual.

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LIST OF ABBREVIATIONS

ABW	-	Absolute Bandwidth
CST	-	Computed Simulation Technology
DGS	-	Defected Ground Structures
EBG	-	Electromagnetic Band Gap
E-field	-	Electric-field
EM	-	Electromagnetic
EMI	-	Electromagnetic Interference
FBW	-	Fractional Bandwidth
FCC	-	Federal Communication Commission
H-field	-	Magnetic-field
LC	-	Inductance-Capacitance
PBG	-	Photonic Band Gap
PCB	-	Printed Circuit Board
RF	-	Radio Frequency
UWB	-	Ultra-Wide Band
VSWR	-	Voltage Standing Wave Ratio
WLAN	-	Wireless Local Area Network

LIST OF SYMBOLS

θ	-	Angle
η_o	-	Intrinsic impedance of free space.
ε_r	-	Dielectric constant or permittivity of dielectric material.
ε_{reff}	-	Effective dielectric constant or effective permittivity of dielectric material.
ε_o	-	Permittivity of free space.
μ_o	-	Permeability of free space.
π	-	Pi (3.14)
Γ	-	Reflection coefficient.
S_{11}	-	Return loss.
S_{21}	-	Transmission coefficient.
c	-	Speed of light in free space.
λ	-	Wavelength.

CHAPTER 1

INTRODUCTION

1.1 Background of The Study

The progressive need of new technology in communication systems to meet the demand of people as the old frequency ranges were insufficient for the number of users and their applications which require high data rates, led to the revelation of a new frequency spectrum that is called "ultra-wide band" (UWB) [1]. This band covers the range from 3.1 GHz to 10.6 GHz, stated by the federal communication commission (FCC) on 2002 [2, 3]. The design of antennas suitable for UWB became significant topic for researchers and various studies were inducted regarding these antennas. UWB antennas became very popular in recent years due to the many advantages they offer.

Many developments have been achieved in UWB technology in last few years. However, some challenges are still available in this technology which are still noteworthy. The most common challenge is the design of UWB antenna. The antenna must be able to transmit and receive signals efficiently and accurately over its allocated bandwidth. The main challenge in designing an UWB antenna is obtaining the extremely large impedance bandwidth while maintaining high radiation efficiency over the entire bandwidth. An UWB antenna must be able to operate over the frequency range of 3.1 GHz to 10.6 GHz. Thus, UWB antennas must achieve an impedance bandwidth of 7.5 GHz. The high radiation efficiency is also imperative in UWB applications to ensure fulfilling the required transmission power spectral density. Therefore, excessive losses in antenna should be reduced in order to make the radiation efficiency as high as possible. Conduction and dielectric losses are very crucial in UWB antenna. Thus, they should be minimized for the purpose of maximizing the radiation efficiency, because the transmission power spectral density of UWB antennas is extremely low. Consequently, any amount of loss incurred by UWB antenna could affect the operation of the system.

Next, the UWB antenna needs to attain a constant group delay through its bandwidth. Group delay is obtained from the derivation of the antenna phase response. If the antenna achieves a linear phase response over its frequency range, a constant group delay will be resulted. This characteristic is substantial because it helps the determination of the quality of pulse transmission and to how extent it might be distorted or dispersed. So, UWB antennas must possess a non-dispersive characteristic in both time and frequency domains. It must also provide narrow, short duration pulses to improve the data rate. Additionally, the radiation pattern of UWB antenna is preferred to be omnidirectional because it provides freedom to the location of transmitter and receiver. Therefore, the half power beam-width must be maximized and the gain and directivity of antenna must be minimized. Another desired feature of UWB antenna is that it has a low profile and can be integrated easily with printed circuit board (PCB) [4]. Various types of antennas can be used for UWB applications. However, the main focus is on microstrip, and planar monopole antennas. These antennas are used with different matching techniques to enhance their bandwidth without degrading the radiation pattern properties [5]. Various matching techniques have been proposed, such as using slot [6], and applying partial ground plane [7]. The preferred UWB antennas are those that have low profile and cost while providing adequate performance in both time and frequency domains [8].

Planar monopole antennas are the most desired candidate for UWB application due to their characteristics such as small size, light weight, simple structure, easy to fabricate, and an almost omnidirectional radiation pattern [9, 10]. And due to the wide bandwidth of UWB systems, UWB antennas may suffer from an electromagnetic interference (EMI) with other narrowband systems such as wireless local area network (WLAN) based on IEEE 802.11a standard operating at 5.8 GHz band inside the UWB frequency range [11]. Therefore, UWB antennas must reject this band to eliminate the interference. One of the advantages of planar monopole antennas is their compatibility to be incorporated with electromagnetic band gap (EBG) structures for improving the performance. The design of EBG structures can be easily accomplished by using planar substrates. Due to their band gap characteristic, EBG structures are used as band rejecters in UWB antennas.

1.2 Problem Statement

One of the serious problems in designing UWB antenna is fitting the size of the antenna for portable devices, because antenna size affects the realized gain and bandwidth. Planar monopole antennas are used to obtain UWB response with a minimal size and reasonable gain. Planar antennas such as microstrip are very popular in UWB application due to their many features such as light weight, low profile, and they can be easily fabricated and integrated with other devices [12]. However, this type of antennas has many drawbacks such as the excitation of undesired surface waves within the dielectric substrate which causes edge radiation [13]. This type of radiation increases the side and back lobes of the radiation pattern which are undesired in point to point communications. This increment in side and back radiation lobes decreases the gain of the antenna [14]. One of the techniques that can improve the antenna performance and reduce the effect of the surface waves is by incorporating the antenna with the EBG structure. From the literature, some of the works that have been on the surface wave reduction by using EBG structure are presented. In this thesis, another application of EBG structure incorporation with antenna is implemented and discussed.

In this research, the design and development of UWB antenna will be presented and discussed. As previously mentioned, the operating bandwidth of UWB antennas is very large. Therefore, UWB system might encounter a possible interference with other narrowband systems working within the UWB frequency range, such as WLAN systems based on IEEE standard 802.11a which operate at 5.8 GHz frequency band. Although UWB antennas radiate signals at low power that is only -41 dBm/Hz, however, nearby systems can still present a source of interference. Consequently, the EBG structures are incorporated with UWB antennas in order to nullify this disturbance to make antennas operate more efficiently. The EBG structure will perform the role of a band rejecter in the UWB antenna without affecting the antenna's radiation properties. Due to its band stop frequency range, EBG rejects the unwanted frequency bands within the UWB operating bandwidth.

1.3 Research Objectives

The main objectives of this research are as follows:

i. The design and simulation of a planar monopole antenna that covers the UWB frequency range from 3.1 GHz to 10.6 GHz with an omnidirectional radiation pattern and a reasonable gain.

ii. The design and simulation of a mushroom like EBG structure that rejects a single band and operates at 5.8 GHz.

iii. The incorporation of the designed antenna and EBG structure in order to enhance the operation of the antenna by rejecting the unwanted 5.8 GHz frequency band.

1.4 Scope of Research

This main focus points of this research are the design and analysis of UWB antenna and EBG structure, and their incorporation. The first part of this project is set to study the concepts of microstrip patch antenna, UWB antenna, and the EBG structure. Then in the second part, an investigation is made on the performance of the EBG structure, and the UWB antenna without and with the EBG. The investigation is performed by using CST simulation software. The UWB antenna is designed to cover the whole frequency range of the UWB band. The mushroom like EBG structure is designed to have its band gap at the unwanted frequency band which is 5.8 GHz. All simulation processes are done by using an FR-4 substrate with a dielectric permittivity (ε_r) of 4.3. The performance of the UWB antenna is concluded by examining the achieved return loss (S_{11}), VSWR, gain, radiation efficiency, and radiation pattern. Whereas the performance of the EBG is done through checking the obtained transmission coefficient (S_{21}), electric (E) and magnetic (H) fields, and surface current. Finally, comparison is made between the UWB antenna before and after adding the

EBG. The established comparison is made in terms of S_{11}, VSWR, gain, radiation efficiency, and radiation pattern.

1.5 Project Outline

The outline of this project is as follows:

In chapter one, the background of the UWB antenna is explained and discussed. the problem statements are mentioned and the gap of the thesis is shown, the objectives of this project are defined and set. And the limitations (scope) of the project are described.

In chapter two, the literature review of this project is presented. The parameters to be considered in designing an antenna are described and demonstrated. The microstrip patch antenna and its types of feeding are explained. The planar UWB antennas and EBG structure are clarified. And previous done work is presented.

In chapter three, the methodology of the project is elaborated. The flow chart of the project is introduced. And the designing process of UWB antenna and mushroom like EBG structure and the simulations are illustrated.

In chapter four, the results obtained from simulations are displayed. The results of the designed UWB antenna and mushroom like EBG are presented and discussed.

In chapter five, the conclusion observed after analysing the obtained results is presented. Moreover, suggestions about future works are mentioned.

1.6 Summary

In this chapter, the background of the UWB antenna, the problem statements, the objectives to be achieved in this project, the scope of the project, and the outline of this thesis have been demonstrated and explained.

REFERENCES

[1] R. J. Fontana, “Recent system applications of short-pulse ultra-wideband (UWB) technology,” *IEEE Transactions on microwave theory and techniques,* vol. 52, no. 9, pp. 2087-2104, 2004.

[2] R. Pillalamarri, J. R. Panda, and R. S. Kshetrimayum, “Printed UWB circular and modified circular disc monopole antennas,” *International Journal of Recent Trends in Engineering,* vol. 1, no. 3, pp. 12, 2009.

[3] Z. Low, J. Cheong, and C. Law, “Low-cost PCB antenna for UWB applications,” *IEEE antennas and wireless propagation letters,* vol. 4, pp. 237-239, 2005.

[4] J. Liang, “Antenna study and design for ultra wideband communication applications,” University of London United Kingdom, 2006.

[5] M. Peyrot-Solis, G. Galvan-Tejada, and H. Jardon-Aguilar, "State of the art in ultra-wideband antennas." pp. 101-105.

[6] Y. Naumar, R. Ngah, and T. A. Rahman, "A small novel ultra wideband antenna with slotted ground plane," *Ultra Wideband*: IntechOpen, 2010.

[7] S. H. Choi, J. K. Park, S. K. Kim, and J. Y. Park, “A new ultra-wideband antenna for UWB applications,” *Microwave and optical technology letters,* vol. 40, no. 5, pp. 399-401, 2004.

[8] Y. Rahayu, “Reconfigurable ultra wideband antenna design and development for wireless communication,” Ph. D Dissertation (unpublished), University Teknologi Malaysia, Malaysia, 2008.

[9] N. P. Agrawall, G. Kumar, and K. Ray, “Wide-band planar monopole antennas,” *IEEE transactions on antennas and propagation,* vol. 46, no. 2, pp. 294-295, 1998.

[10] C.-Y. Wu, C.-L. Tang, and A.-C. Chen, "UWB chip antenna design using LTCC multilayer technology for mobile applications." p. 3 pp.

[11] K. Thomas, and M. Sreenivasan, “Compact CPW-fed dual-band antenna,” *Electronics Letters,* vol. 46, no. 1, pp. 13-14, 2010.

[12] A. Abdelaziz, “Improving the performance of an antenna array by using radar absorbing cover,” *Progress In Electromagnetics Research,* vol. 1, pp. 129-138, 2008.

[13] M. A. Khayat, J. T. Williams, D. R. Jackson, and S. A. Long, "Mutual coupling between reduced surface-wave microstrip antennas," *IEEE Transactions on Antennas and Propagation,* vol. 48, no. 10, pp. 1581-1593, 2000.

[14] F. Yang, and Y. Rahmat-Samii, "Mutual coupling reduction of microstrip antennas using electromagnetic band-gap structure." pp. 478-481.

[15] L. Peng, and C.-L. Ruan, "UWB band-notched monopole antenna design using electromagnetic-bandgap structures," *IEEE transactions on microwave theory and techniques,* vol. 59, no. 4, pp. 1074-1081, 2011.

[16] E. Docket, *Docket 98–153, FCC, Revision of part 15 of the commissions rules regarding ultra-wideband transmission systems,* Technical Report, 2002.

[17] H. G. Schantz, "A brief history of UWB antennas," *IEEE Aerospace and Electronic Systems Magazine,* vol. 19, no. 4, pp. 22-26, 2004.

[18] R. Fontana, "A brief history of UWB communications. Multispectral Solutions Inc," Kluwer Academic/Plenum Publishers, 2000.

[19] R. A. Abdulhasan, "Design of microstrip ultra wide band antenna with two notch filters for wireless communication," Universiti Tun Hussein Onn Malaysia, 2015.

[20] P.-S. Kildal, *Foundations of antenna engineering: a unified approach for line-of-sight and multipath*: Artech House, 2015.

[21] C. A. Balanis, *Antenna theory: analysis and design*: John wiley & sons, 2016.

[22] F. T. Ulaby, "Fundamentals of applied electromagnetics(1999 revised and enlarged edition)(Book)," *Upper Saddle River, NJ: Prentice-Hall, Inc, 1999.*, 1999.

[23] C. Wolff. "Antennas," 25-October, 2019.

[24] G. M. Galvan-Tejada, M. A. Peyrot-Solis, and H. J. Aguilar, *Ultra wideband antennas: design, methodologies, and performance*: CRC Press, 2015.

[25] R. Nave. "Methods for achieving polarization," 25- OCtober, 2019.

[26] M. Alibakhshi-Kenari, M. Naser-Moghadasi, B. S. Virdee, A. Andújar, and J. Anguera, "Compact antenna based on a composite right/left-handed transmission line," *Microwave and Optical Technology Letters,* vol. 57, no. 8, pp. 1785-1788, 2015.

[27] M. A. Kenari, “New traveling-wave antenna resonating at 6 GHz based on artificial transmission line metamaterial structures for RF portable devices,” *Open Journal of Antennas and Propagation,* vol. 1, no. 02, pp. 5, 2013.

[28] R. Collin, “Field Theory of Guided Waves 2nd edn (New York: IEEE),” 1991.

[29] D. M. Pozar, *Microwave and RF design of wireless systems*: Wiley Publishing, 2000.

[30] M. Alibakhshikenari, M. Naser-Moghadasi, R. A. Sadeghzadeh, B. S. Virdee, and E. Limiti, “Printed Planar Antenna Designs Based on Metamaterial Unit-Cells for Broadband Wireless Communication Systems,” *Microstrip Antennas: Trends in Research on,* pp. 111, 2017.

[31] J. L. Volakis, R. C. Johnson, and H. Jasik, “Antenna engineering handbook,” 2007.

[32] Z. N. Chen, M. J. Ammann, X. Qing, X. H. Wu, T. S. See, and A. Cai, “Planar antennas,” *IEEE Microwave Magazine,* vol. 7, no. 6, pp. 63-73, 2006.

[33] R. Azim, A. T. Mobashsher, M. T. Islam, and N. Misran, "Compact planar antenna for UWB applications." pp. 1987-1990.

[34] A. Pathmanathan, and L. C. Nadeson, “Ultra Wide-band (UWB) Microstrip Patch Antenna,” Tesis Doktor Falsafah. Universiti Teknologi Malaysia, 2006.

[35] M. Ammann, and Z. N. Chen, “An asymmetrical feed arrangement for improved impedance bandwidth of planar monopole antennas,” *Microwave and Optical technology letters,* vol. 40, no. 2, pp. 156-158, 2004.

[36] A. A. Eldek, “Numerical analysis of a small ultra wideband microstrip-fed tap monopole antenna,” *Progress In Electromagnetics Research,* vol. 65, pp. 59-69, 2006.

[37] E. Yablonovitch, “Photonic crystals,” *Journal of Modern Optics,* vol. 41, no. 2, pp. 173-194, 1994.

[38] Y. Rahmat-Samii, and H. Mosallaei, “Electromagnetic band-gap structures: classification, characterization, and applications,” 2001.

[39] Y. Rahmat-Samii, “Ebg structures for low profile antenna designs: What have we learned,” 2007.

[40] A. S. Barlevy, and Y. Rahmat-Samii, “Characterization of electromagnetic band-gaps composed of multiple periodic tripods with interconnecting vias:

Concept, analysis, and design," *IEEE Transactions on antennas and propagation,* vol. 49, no. 3, pp. 343-353, 2001.

[41] E. Özbay, A. Abeyta, G. Tuttle, M. Tringides, R. Biswas, C. Chan, C. Soukoulis, and K. Ho, "Measurement of a three-dimensional photonic band gap in a crystal structure made of dielectric rods," *Physical Review B,* vol. 50, no. 3, pp. 1945, 1994.

[42] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and techniques,* vol. 47, no. 11, pp. 2059-2074, 1999.

[43] F.-R. Yang, K.-P. Ma, Y. Qian, and T. Itoh, "A uniplanar compact photonic-bandgap (UC-PBG) structure and its applications for microwave circuits," *IEEE Transactions on microwave theory and techniques,* vol. 47, no. 8, pp. 1509-1514, 1999.

[44] F. Yang, and Y. Rahmat-Samii, *Electromagnetic band gap structures in antenna engineering*: Cambridge university press Cambridge, UK, 2009.

[45] O. Ayop, and M. K. A. Rahim, "Analysis of mushroom-like electromagnetic band gap structure using suspended transmission line technique." pp. 258-261.

[46] A. Azarbar, and J. Ghalibafan, "A compact low-permittivity dual-layer EBG structure for mutual coupling reduction," *international journal of antennas and propagation,* vol. 2011, 2011.

[47] N. Rao, and D. K. Vishwakarma, "Gain enhancement of microstrip patch antenna using Sierpinski fractal-shaped EBG," *International Journal of Microwave and Wireless Technologies,* vol. 8, no. 6, pp. 915-919, 2016.

[48] S. Sun, and L. Zhu, "Periodic finite-ground microstrip line with high-impedance offset sections: enhanced electromagnetic bandgap." pp. 383-386.

[49] H. C. Fernandes, D. B. Brito, and J. L. Medeiros, "EBG substrate in unilateral fin line resonator." pp. 530-534.

[50] M. Karim, A. Liu, A. Alphones, and X. Zhang, "Low-pass filter using a hybrid EBG structure," *Microwave and Optical Technology Letters,* vol. 45, no. 2, pp. 95-98, 2005.

[51] A. Danideh, A. A. Lotfi-Neyestanak, M. Naser-Moghadasi, and G. R. Dadashzadeh, "Compact slot antenna with EBG feeding line for WLAN applications," *Progress In Electromagnetics Research,* vol. 10, pp. 87-99, 2009.

[52] M. P. Kesler, J. G. Maloney, B. L. Shirley, and G. S. Smith, “Antenna design with the use of photonic band-gap materials as all-dielectric planar reflectors,” *Microwave and optical technology letters,* vol. 11, no. 4, pp. 169-174, 1996.

[53] I. Gupta, and A. Ksienski, “Effect of mutual coupling on the performance of adaptive arrays,” *IEEE Transactions on Antennas and Propagation,* vol. 31, no. 5, pp. 785-791, 1983.

[54] T. Rukmini, “EBG Antennas: Their Design and Performance Analysis for Wireless Applications,” 2012.

[55] N. Jaglan, S. D. Gupta, B. K. Kanaujia, and S. Srivastava, “Band notched UWB circular monopole antenna with inductance enhanced modified mushroom EBG structures,” *Wireless Networks,* vol. 24, no. 2, pp. 383-393, 2018.

[56] F. Alizadeh, J. Nourinia, C. Ghobadi, and B. Mohammadi, "A dual-band rejection UWB antenna using EBG." pp. 0192-0193.

[57] K. Alshamaileh, M. Almalkawi, and V. Devabhaktuni, “Dual band-notched microstrip-fed Vivaldi antenna utilizing compact EBG structures,” *International Journal of Antennas and Propagation,* vol. 2015, 2015.

[58] A. Yadav, N. Temani, M. Sharma, and R. Yadav, "A Novel EBG-Loaded Dual Band-Notched UWB Antenna," *Optical and Wireless Technologies,* pp. 79-87: Springer, 2020.

[59] S. Peddakrishna, and T. Khan, “Design of UWB monopole antenna with dual notched band characteristics by using π-shaped slot and EBG resonator,” *AEU-International Journal of Electronics and Communications,* vol. 96, pp. 107-112, 2018.

[60] R. Chandel, A. Gautam, and B. K. Kanaujia, "Annular-ring antenna for UWB applications." pp. 1-2.

[61] M. G. N. Alsath, and M. Kanagasabai, “Compact UWB monopole antenna for automotive communications,” *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 9, pp. 4204-4208, 2015.

[62] A. M. Abdelraheem, and M. A. Abdalla, “Compact curved half circular disc-monopole UWB antenna,” *International Journal of Microwave and Wireless Technologies,* vol. 8, no. 2, pp. 283-290, 2016.

[63] I. B. Vendik, A. Rusakov, K. Kanjanasit, J. Hong, and D. Filonov, “Ultrawideband (UWB) planar antenna with single-, dual-, and triple-band notched characteristic based on electric ring resonator,” *IEEE Antennas and wireless propagation letters,* vol. 16, pp. 1597-1600, 2017.

[64] A. K. Gautam, S. Yadav, and B. K. Kanaujia, “A CPW-fed compact UWB microstrip antenna,” *IEEE Antennas and Wireless propagation letters*, vol. 12, pp. 151-154, 2013.

[65] G. Singh, and U. Singh, "Dual Band Rejected Low Profile Planar Monopole Antenna for UWB Application." pp. 534-538.

[66] H. F. Shaban, H. A. Elmikaty, and A. A. Shaalan, “Study the effects of electromagnetic band-gap (EBG) substrate on two patch microstrip antenna,” *Progress In Electromagnetics Research*, vol. 10, pp. 55-74, 2008.

[67] R. Garg, P. Bhartia, I. J. Bahl, and A. Ittipiboon, *Microstrip antenna design handbook*: Artech house, 2001.